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13. ABSTRACT *(Maximum 200 Words)*
Real-time, wide band information storage and signal processing devices are critical to many military and commercial systems. Optical coherent transient technology has the potential to perform real-time storage and continuous signal processing at data rates up to a terahertz, with storage/pattern densities on the order of a terabit per centimeter squared, and with data block sizes/time-bandwidth products well over 10000. These attributes coupled with spatial selectivity and the ability to process amplitude, phase, and frequency modulated signals makes coherent transients an extremely versatile technology. Applications include target and pattern recognition; multi-dimensional cache memory; high density, high bandwidth database memory, associative memory, and look-up tables; secure communications; interior memory for optical networks; real-time address decoder; all optical passive routing of data; header stripper/isolator for network packets; and dynamic pulse shaping and distortion compensation.

The research under this grant included work on true-time delay regenerators, power induced time-shifts, chirped pulse programming of coherent transient true-time-delay devices, orthogonal code development, recall efficiencies in optically thick media (non-inverted) and inverted media, modeling and characterization of gated systems, and routing and processing of optical waveforms with structured surface gratings. The grant was terminated after one year due to Prof. Babbitt's move to Montana State University.

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Abstract

Real-time, wide band information storage and signal processing devices are critical to many military and commercial systems. Optical coherent transient technology has the potential to perform real-time storage and continuous signal processing at data rates up to a terahertz, with storage/pattern densities on the order of a terabit per centimeter squared, and with data block sizes/time-bandwidth products well over 10000. These attributes, coupled with spatial selectivity and the ability to process amplitude, phase, and frequency modulated signals makes coherent transients an extremely versatile technology. Previously proposed applications include target and pattern recognition; multi-dimensional cache memory; high density, high bandwidth database memory, associative memory, and look-up tables; secure communications; interior memory for optical networks; real-time address decoder; all optical passive routing of data; header stripper/isolator for network packets; and dynamic pulse shaping and distortion compensation.

Objectives of grant

The main objective of the research under this grant is to advance beyond the traditional implementations and applications of coherent transients and explores novel concepts that exploit the processing and non-linear behaviors of coherent transient systems. These area include 1) true-time delay regenerators, 2) true-time-delay adaptive beamforming 3) continuously programmed continuous processor, 4) feedback and learning, 5) inversion and gain gratings, 6) index modulation, 7) single sideband and frequency modulation, and 8) bilinear transforms and circuit modeling. The proposed research also explores critical issues that significantly impact the development of practical coherent transient systems. These include: 1) orthogonal code development 2) modeling and characterization of gated systems, and 3) cryocooler evaluation. In addition, we have expanded our objective to include the study of recall efficiencies in optically thick media (non-inverted) as per conversations with Dr. Alan E. Craig. As the grant was terminated after one year due to Prof. Babbitt's move to Montana State University, several of the objectives were not pursued, but instead transferred to the new grant at Montana State University.

Summary

This grant was started in February of 1997. Prof. Babbitt, the principal investigator, moved to Montana State University in August of 1997. With the consent of AFOSR, the first year of the grant was continued with Prof. Leung Tsang the Department of Electrical Engineering at the University of Washington, acting the new principal investigator. Prof. Tsang became the official advisor of graduate students Molly Byrne and Carrie Cornish, while Prof. Babbitt remained their technical advisor. The research objectives of this grant that could not be accomplished due to the short time scale were continued under grant

F49620-98-1-0283, awarded to Prof. Babbitt at Montana State University with a subcontract to the University of Washington to continue the support of Byrne, Cornish, and Tsang.

Support for the research under this grant was augmented by ASSERT grant F49620-95-1-068 and DURIP grant F49620-95-1-047. The performance period of this grant overlapped the start of grant F49620-98-1-0283, which supports Prof. Babbitt's time and laboratory at Montana State University. Graduate students Byrne and Cornish are doing their experimental work in Prof. Babbitt's laboratory at Montana State University

The bulk of the findings has been published or has been submitted for publication in archival journals. Summaries of the published findings are given in this report with references to the publications. For those areas not yet published, details of the findings or the status of work in progress are reported here.

Statement of Work

-We will carry out an analytical and experimental investigation of coherent transient true-time delay regenerators. We will investigate delay resolution, wide-band operation, simultaneous processing and delay, multicast beam forming, spatial multiplexing of delays, serial programming and parallel access of delays, frequency division multiplexed delays, frequency chirped programming pulses, true-time delay receiver/processors, and true-time delay system architectures.

-We will investigate the implementation of beamforming using spatial-spectral holographic processing. This work will be done in collaboration with Prof. Kelvin Wagner of the University of Colorado at Boulder.

-We will analyze and simulate the operation of a continuously programmed continuous processor (CPCP). We will experimentally demonstrate the CPCP and evaluate its performance.

-We will analyze the gain and processing capabilities of various coherent transient system configurations and evaluate their applicability to feedback loops, neural networks, associative recall, and adaptive learning algorithms.

-We will investigate the storage and processing of temporally structured (information) pulses in inverted and gated media and conduct experiments to verify our findings.

-We will examine the effects of index modulation on the temporal and spatial fidelity of coherent transient output signals. We will explore possible advantageous uses of index modulation in creating more efficient (absorption free) spectral gratings.

-We will investigate the merits of employing single sideband and frequency modulation in coherent transient system. We will conduct experimental demonstrations of the modulation techniques that have merit.

-We will explore the applicability of bilinear transforms to the optical Maxwell-Bloch equations under the conditions applicable to coherent transient systems. We will develop and incorporate models of coherent transients into existing circuit modeling programs and demonstrate their use in evaluating coherent transient systems.

-We plan to develop codes sets for use in large (on the order of 1000) time-bandwidth products. We will evaluate and demonstrate the use of these codes in coherent transient systems.

-We will continue our research into developing analytical models of coherent transient systems that employ photon gated materials with the purpose of guiding materials growers in material development. We will characterize promising gated materials.

-We will evaluate the cooling requirements of coherent transient systems and the cooling capabilities of existing and planned cryogenic systems in order to determine the best cryogenic technology(ies) for various coherent transient systems. This work will be done in collaboration with Prof. Zameer Hasan of Temple University.

Achievements/New Findings

Photon Echo Data Recall Efficiencies

The most significant result is that theoretical prediction that data recall efficiencies much greater than unity are achievable in optically thick inverted media while maintaining high fidelity in the recall of data signals. Enhanced efficiencies are critical to making coherent transient devices practicable. These results are significant in that they may lead to highly efficiency, large time-bandwidth product, broad band processing, routing, and storage devices. The results were in the paper "Efficient waveform recall in absorbing media," presented by C. S. Cornish at the 1998 Conference on Lasers and Electro-Optics and reported in the journal publication by M. Azadeh, C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang , "Efficient photon echoes in optically thick media," in Physical Review A 57, 4662-8. We have now demonstrated echo efficiencies of 50% in barium vapor and expect further refinements of our experiment to yield echo efficiencies exceeding unity. Further research in this area will be done in doped crystal, specifically Tm: YAG crystals. Unity efficiency would mean the devices can be inserted with minimal insertion loss and possible gain, allowing for cascading devices and achieving feedback and adaptation.

Power induced time-shift of coherent transient output signals

It was found that there is a shift in the timing of the output signals of coherent transient true-time-delay regenerators. A paper has been prepared for publication on the role of non-linearities in the material excitation of the delay timing. It was found that the delayed output of a coherent transient true-time-delay regenerator was shifted as a function of the strength of the input pulses. It was found that as the pulse area of the programming pulses or read pulse approached pi/2, significant shift occurred in the delayed output. The sign of the temporal shift depended on which pulse was being varied and it was found that this shift was related to whether the information about the coherent transient output of interest was being transferred from a population to a coherence or from a coherence to a population. These shifts were analyzed experimentally, analytically, and through numerical simulation and are now well characterized. The maximum shift is about 10% of the duration of the programming pulses and should not significantly affect the operation of coherent transient true time delay. In addition, since the shifts are well understood, this information can be used to compensate the programming of true-time-delay regenerators. A manuscript is in preparation. The results have were presented by K. D. Merkel in the paper "Temporal dependence of coherent transient regenerated true-time-delays on intensity of applied pulses" at the 1998 Conference on Lasers and Electro-Optics. Further research on similar effects when programming with chirped pulses would be worth pursuing.

Chirped pulse programming of coherent transient true-time-delay devices

It was proposed and demonstrated that chirped reference pulses can be used in the programming of optical coherent transient true-time delays. Coherent transient true-time delay devices have the ability to simultaneously, and continuously process several hundred delays over a broad bandwidth with fine temporal resolution. Such devices will find application in phased array antennas and will enable wide angle (> 45 degrees) beamsteering of wide-bandwidth (> 10GHz) for multi-element (> 1000) arrays. Multicasting and simultaneous delay and temporal processing capabilities are additional features. Chirped pulses an order of magnitude longer than the delay resolution desired can be used to introduce precise delays. Varying the temporal separation between the chirped reference pulses or more significantly by introducing a frequency shift of one or both of the chirped reference pulses can program delays. The use of frequency shift programming enables fine delay resolution that is controlled simply with a frequency shifting device. The change in delay is proportional to the frequency shift (it equals the frequency shift divided by the chirp rate). This work was documented in the paper by K. D. Merkel and W. R. Babbitt, "Chirped-pulse programming of optical coherent transient true-time delays," Optics Letters 23, 528-30 (1998) and presented by K. D. Merkel in the paper "Chirped Pulse Programming of Spatial-Spectral Holographic True-Time Delays" at the The Eighth Annual DARPA Symposium on Photonic Systems for Antenna Applications in Monterey, CA.

Routing and processing of optical waveforms with structured surface gratings

A paper was submitted with Prof. Tom Mossberg of the University of Oregon on the routing of temporally encoded pulses via spectral filtering using only a single spatial surface grating. These devices could act as routers as well as address header decoder in terahertz communication systems. W.R. Babbitt and T. W. Mossberg, "Optical waveform processing and routing with structured surface gratings," Optics Comm. 148, 23-26 (1998). The results of this work will be included in follow on to the patent "Apparatus and methods for routing of optical beams via time-domain spatial-spectral filtering."

Development of codes for spatial-spectral holographic processors

In the area of code development, Prof. Jim Ritcey and Xiaodong Li have found several favorable poly-phase code sets. This is significant as poly-phase codes can offer a greater degree of security in communication as well as affording a greater number of users in a limit bandwidth space. Optical coherent transient are the only technology we know of that can process poly-phase coded communications in real-time at multi-gigahertz rates. The results of this work we presented by W. R. Babbitt and published in the Proceedings of the SPIE, Multimedia Networks: Security, Displays, Terminals, and Gateways in the paper "All-optical signal encoder-decoder for secure communications."

Echoes in an Inverted Media

As reported in the final report of F49620-93-1-0513, the enhanced efficiencies that are achievable in inverted media has been shown via computer simulation. The most significant result is that data recall efficiencies much greater than unity are achievable in optically thick inverted media while maintaining high fidelity. Updated results of this work were presented by W. R. Babbitt in the talk "Coherent Transients in Inverted Media," at the Frontiers of Applications of Photospectral Holeburning Workshop. Experiments to verify these results were attempted tried in barium vapor. However, vapor samples are not suitable for this demonstrations due to the long coherence lifetime compared to the excited population decay. Schemes for demonstrating this in doped crystal are being explored.

Personnel

Degrees awarded:

Kristian D. Merkel, Ph.D. in Electrical Engineering, June 1998

Personnel Supported (all at the University of Washington):

Wm .Randall Babbitt, Research Assistant Professor, Principal Investigator
Mohammed Azadeh, Graduate Research Assistant
Molly J. Byrne, Graduate Research Assistant (under AASERT grant)
Kristian D. Merkel, Graduate Research Assistant (partly under AASERT grant)
Carrie S. Cornish, Graduate Research Assistant (partly under AASERT grant)
Jim Ritcey, Associate Professor, Co-investigator
Xiaodong Li, Graduate Research Assistant

Publications and Interactions

Refereed Journal Publications

K. D. Merkel and W. R. Babbitt, "Chirped-pulse programming of optical coherent transient true-time delays," Optics Letters 23, 528-30 (1998).

W.R. Babbitt and T. W. Mossberg, "Optical waveform processing and routing with structured surface gratings," Optics Comm. 148, 23-26 (1998).

M. Azadeh, C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang , "Efficient photon echoes in optically thick media," Physical Review A 57, 4662-8 (1998).

Refereed Conference Publications

K. D. Merkel and W. R. Babbitt, "Chirped Pulse Programming of Spatial-Spectral Holographic True-Time Delays," The Eighth Annual DARPA Symposium on Photonic Systems for Antenna Applications, January 14-16, 1998, DTIC# ADB 223444 PAA.

K. D. Merkel and W. R. Babbitt, "Temporal dependence of coherent transient regenerated true-time-delays on intensity of applied pulses," in Conference on Lasers and Electro-Optics, Vol. 6, 1998 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1998) pp 171. San Francisco, Ca., May 3-8, 1998.

C. S. Cornish, M. Azadeh, W. R. Babbitt, and L. Tsang "Efficient waveform recall in absorbing media," in Conference on Lasers and Electro-Optics, Vol. 6, 1998 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1998) pp 214-5. San Francisco, May 3-8, 1998.

Invited Conference Publications

W. R. Babbitt, "Spatial-Spectral Holographic Memories, Processor, and Routers," in *Optics in Computing*, Vol. 8, 1997 OSA Technical Digest Series (OSA, Washington DC, 1997), pp172-174, Incline Village, NV, March 16-21, 1997.

W. R. Babbitt, "Spatial-Spectral Holographic Routing and Processing Devices", in Conference on Lasers and Electro-Optics, Vol.11, 1997 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1997) pp 213. Baltimore, MD, May 18-23, 1997.

Non-Refereed Conferences Proceedings

W. R. Babbitt, A. Mohan, and J. A. Ritcey, "All-optical signal encoder-decoder for secure communications," Proceedings of the SPIE, Multimedia Networks: Security, Displays, Terminals, and Gateways, Dallas, TX, Nov. 4-5 1997, Vol. 3228, pp. 354-65 (1998).

C. S. Cornish, M. Azadeh, W.R. Babbitt, and L. Tsang, "Efficient waveform recall in absorbing media," Proceedings of the SPIE, Advanced Optical Memories and Interfaces to Computer Storage, San Diego, CA, July 22-24, 1998, Vol. 3468, paper 3468-26 (1998).

Workshop Presentations and Lectures

W. R. Babbitt and M. Azadeh, "Coherent Transients in Inverted Media," Frontiers of Applications of Photospectral Holeburning Workshop, Big Sky, MT, Feb. 16-19, 1997.

Patents Issued and Filed

W. R. Babbitt and T. W. Mossberg, "Apparatus and methods for routing of optical beams via time-domain spatial-spectral filtering," U. S. Patent No. 5,812,318 (September 22, 1998).

Transitions

Templex Technology of Eugene, OR has negotiated an agreement with the University of Washington for licensing rights to U. S. Patent No. 5,239,548 (Babbitt and Bell, August 24, 1993), "An optical signal processor for processing continuous signal data") and U. S. Patent application filed March 13, 1995 (Babbitt and Mossberg, "Apparatus and methods for routing of optical beams via time-domain spatial-spectral filtering") for use in the development of spectral-spatial holographic routers and memory.

Web Sites and Listserves Maintained

Persistent Spectral Holeburning Web Page and Bulletin Board listserve
Web site: http://weber.u.washington.edu/~rbabbitt/pshb.html
Listserve: pshb@ee.washington.edu